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Feasibility study of desalination plant powered by SMR

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A B S T R A C T

The aim of the paper is to assess the feasibility of nuclear desalination, which will be obtained using both electricity and heat generated by nuclear power plant to remove salt and minerals from seawater. The integration of a water desalination plant into a small and modular nuclear power plant is described by considering a combination of a variety of seawater desalination co-generation configurations/ techniques (thermal or membrane in single or hybrid mode) to show they are successfully coupled with SMRs (of different types) to produce water and electricity at different scales. Running SMRs as base load plants is more economical and simpler than requiring them to follow load. Therefore, in a cogeneration mode and while grid load is low, they may run at full capacity even if their capacity exceeds water demands.

The proposed solution was numerically investigated from both thermodynamic and economic points of view using the Desalination Economic Evaluation Program (DEEP) software made available by the IAEA.

The study highlights the role of factors such as site characteristics, plant capacity, feed/product-water quality, energy costs, in affecting the economics of desalination regardless of the energy source used. The economics of nuclear desalination has been found to be competitive with other desalination techniques driven by other sources of energy. Results show that e.g., for an average per capita electricity consumption of 4.7 MWh/year and 80.3 m^3/year of water, the CAREM25 reactor coupled to a desalination plant could produce electricity for 35,000 inhabitants and water for domestic use for 200,000 inhabitants.

1. Introduction

Nuclear desalination is gaining interest worldwide, as it is expected that the number of desalination plants will increase in the near future to meet the ever-increasing demand for drinking water by the world population. The need of water resources is expected to increase together with the population growth (Fig. 1) and seawater desalination, which is often achieved by using membrane separation or heating the sea water until the freshwater is vaporized and salts are left behind (Schmidt and Gude, 2021), represents an important option for satisfying current and future demands for fresh water in arid and semi-arid regions with close proximity to the sea.

Developing and providing adequate water resources, their conservation and preservation have become fundamental problem. From that it appears how important is to investigate the possibility of (and support for) seawater desalination using nuclear energy. Moreover, desalination achieved with fossil fuel would not be compatible with sustainable development.

Nuclear desalination (ND) can instead significantly contribute to achieving the sustainability objectives by minimizing the environmental impact, removing some of the impediments for the use renewable energy sources. ND involves three technologies: nuclear, desalination and their coupling system.

The idea to use nuclear energy for water desalinization is not new as it has been around for almost 50 years. The BN-350 (135 MWe of electric power) sodium-cooled fast reactor in Kazakhstan successfully produced more than 80,000 m^3/d of drinkable water for more than 26 years. It was one of earlier examples proving the ND feasibility and reliability. In Japan, about 10 desalination units coupled to PWRs were operated with a production of drinkable water of about 14,000 m^3/d. Though sufficient experience was gained over more than 150 reactor-years of experience mainly in Kazakhstan, India, Japan, and USA, demonstrating it is technically feasible, ND option has never achieved wide application (International Atomic Energy Agency, 2010) (Yan et al., 2017). Table 1 provides an overview of the status of nuclear desalination in the world.

Numerous studies can be found in the scientific literature on seawater desalination, but they focus mainly on the environmental (consequences/adverse) impacts of the intake and the liquid multi-component waste discharge on the marine environment. Only few studies deal with the nuclear desalination technologies. Al-Othman et al., 2019, e.g., reviewed extensively the advances and technical features of ND plants highlighting that the SMRs are advantageous as they offer the moderate space for installation, shorter time for construction, have less capital cost and safe operation (Al-Othman, 2019).

Jung et al. 2014 evaluated the feasibility to couple two selected nuclear thermal desalination systems with a seawater thermal

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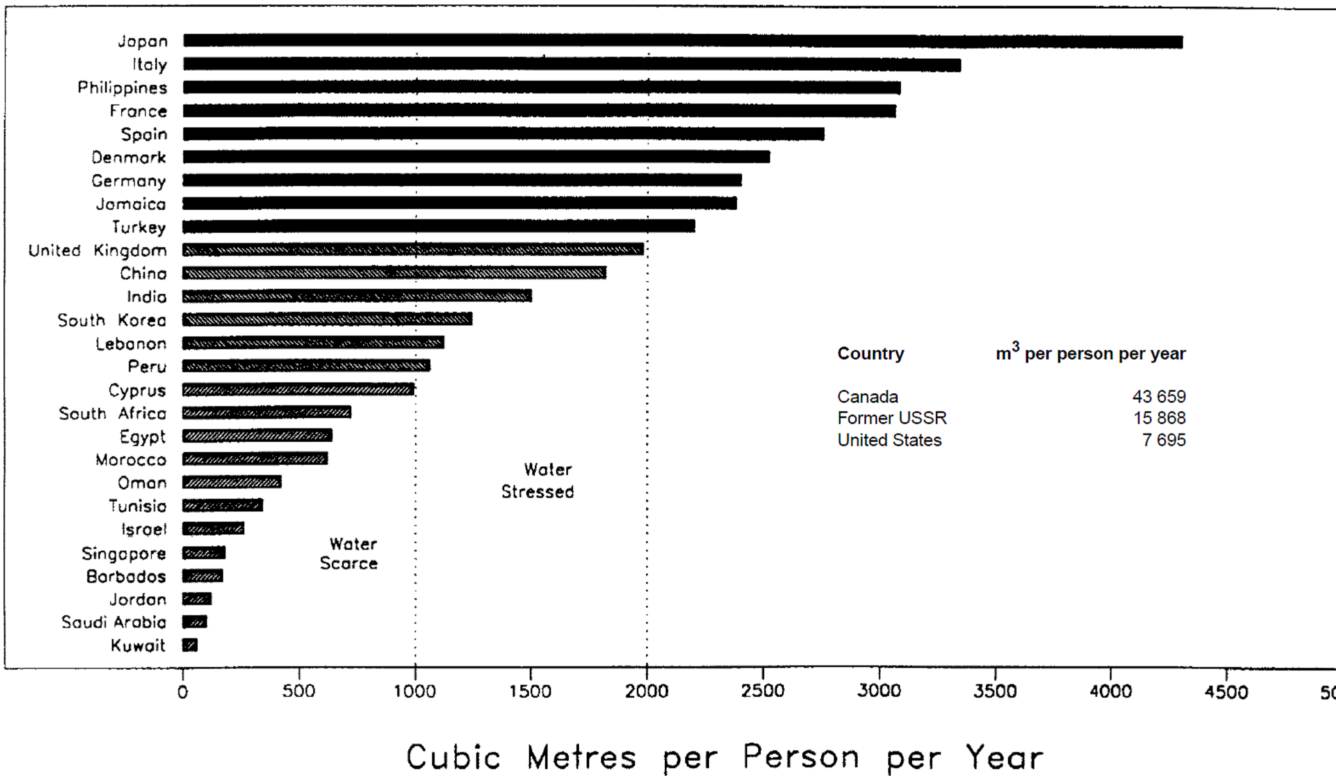

Fig. 1. IAEA forecast of hydrologists' concept of Water Stress Index (i.e. approximate minimum level of water required per capita to maintain an adequate quality of life in a moderately developed country in an arid zone) with illustration of Countries expected to experience water stress or scarcity by 2025 (from International Atomic Energy Agency (2000)).

Table 8
Main results from the DEEP analysis.

	CC GAS RO	CAREM 25 RO	SMART RO	MED	MED + RO	MSF	MSF + RO
Electricity Production [GWh/y]	227	223	688	688	688	688	688
Power Grid [MWe]	22	21	81	75	79	63	74
Power Cost [$/MWh]	64.3	35.9	36	36	36	36	36
Water Production [Mm^3/y]	15.77	15.77	13.14	11.83	12.63	11.83	12.63
Water Cost [$/$m^3$]	0.73	0.64	0.63	0.81	0.68	1.12	0.8
Water Salinity [ppm]	168	168	221	25	150	25	150
Lifecycle Emissions [Mtn/y]	91	6	20	20	20	20	20
Combined Availability [%]	81	81	81	81	81	81	81
Power for Desalination [MWe]	7	7	6	3	5	5	5
Power Lost [-]	–	–	–	9	3.5	19	7.3
GOR [-]	–	–	–	10	10	9	9
Stages [-]	–	–	–	13	13	31	31
Recovery Ratio [%]	43	43	36	50	50	50	50
					36		36

desalination plant. The obtained results indicate that the operating pressure of the motive steam is the design parameter that mostly affects the performance of the desalination plant (Jung, 2014).

This study describes the integration between a novel nuclear SMR and a water desalination plant for electricity and freshwater productions so as to create a multi-energy complementary system. The most common seawater desalination co-generation configurations/ techniques are described in Section 2. Section 3 describes the coupling of thermal or membrane (in single or hybrid mode) techniques with SMRs (of different types) to produce water and electricity at different scales, and the analysis of technical and economic feasibility of nuclear desalinization that was carried out by the Desalination Economic Evaluation Program (DEEP) software made available by IAEA (DEEP, 2000). These analyses were carried out considering both the CAREM25 and SMART nuclear reactors, having 32 MWe and 100 MWe electrical power respectively. As described in detail in the following, the objective of the performed analyses is to verify how these SMRs can produce respectively 48,000 m^3/d and 40,000 m^3/d of water by using one of the most widely used desalination technologies in the industry.

2. Seawater desalination process

Desalination consists in the removal of salts present in salt water, i.e., sea water, to obtain fresh water. The desalination plant is a complex plant consisting of seawater intake system, pretreatment system, desalination equipment and associated equipment, product water treatment plant and other auxiliaries. Fig. 2 shows a generic example of a ND plant.

The main desalination plant parameters are (Kazmerski and Al-

Table 1
Nuclear desalinization plants worldwide (Schmidt and Gude, 2021).

Plant name	Location	Gross Power [MW (e)]	Capacity [m^3/d]	Energy/ Desalination
Shevchenko*	Aktau, Kazakhstan	150	80 000–145 000	LMFBR/ MSF&MED
Itaka-1,2	Ehime, Japan	566	2000	PWR/MSF
Itaka-3	Ehime, Japan	890	2000	PWR/RO
Ohi-1,2	Fukui, Japan	2 x 1175	3900	PWR/MSF
Ohi-3,4	Fukui, Japan	1 x 1180	2600	PWR/RO
Genkai −4	Fukuoka, Japan	1180	1000	PWR/RO
Genkai-3,4	Fukuoka, Japan	2 x 1180	1000	PWR/MED
Takahama-3,4	Fukui, Japan	2 x 870	1000	PWR/RO
NDDP	Kalpakkam, India	170	6300	PHWR/ Hyb. MSF-RO
LTE	Trombay, India	40 [MW(t)]	30	PHWR/LTE
Diablo Canyon	San Luis Obispo, USA	2 x 1100	2180	PWR/RO

* Shevchenko was shut down in 1999, after 26 years operation.

Karaghouli, 2013.1016/j.rser.2012.12.064.):

- Electrical and Thermal Energy Consumption [kWh/m^3] referred to the volume of the permeate water, which are defined by the ratio between the input electrical or thermal power and the volume of the purified water.
- GOR [-] i.e., Gain Output Ratio, which indicates the ratio between the distilled water flow produced and the required inlet steam flow.
- RR [%] i.e., Recovery Ratio, which is the ratio between the flow rate of desalinated water produced and the flow rate of input water to be desalinated.

The most common conventional desalination technologies are divided in thermal (TP) and non-thermal processes (membrane processes- MP): both are energy-intensive processes. Therefore, they can be listed by the type of energy that drives them into:

a) Thermal Energy processes
   - Simple Stills (SS)
   - Multi-Effect Distillation (MED)
   - Multi-Stage Flash Evaporation (MSF)
   - Thermal Vapor Compression (TVC)

b) Mechanical Energy processes
   - Mechanical Vapor Compression (MVC)
   - Reverse Osmosis (RO)

c) Electrical Energy process
   - Electrodialysis (ED)

In six of these processes, the fresh water is removed from the feed stream, leaving behind a more concentrated brine; the only one that removes the salt leaving behind a purified feed stream is the ED.

All the DP require heat and electricity according to their technology, capacity, and operation. Moreover, in the dual-purpose ones, the energy needed is supplied from the power plant.

The most practiced processes are the MSF and MED and the RO: the formers desalinate water through evaporation and condensation, the latter thanks to reverse osmosis and osmotic membranes that separate the salt from the water making it completely free of mineral salts and solid particles. The obtainable products by means of such techniques are the desalinated water, i.e., permeate, for civilian use and the residual water with a higher concentration of salts, i.e., brine, to be discarded. The MED instead is among the oldest desalination technologies: its main components are preheaters, distillation units and condensers (Al-Shammiri and Safar, 1999).

Firstly, the salt water is heated up to the saturation temperature for

Table 2
Operating performances of the most practiced desalination plants (International Atomic Energy Agency, 2010).

	MED	MSF	RO
Max Brine Temperature [°C][b]	55 ÷ 70	90 ÷ 120	T_{room}
Thermal energy consumption [MJ/m^3]	145 ÷ 230	190 ÷ 282	–
Electrical energy consumption [kWh/m^3]	2 ÷ 2.5	2.5 ÷ 5	4 ÷ 6
Equivalent Electrical to Thermal Energy [kWh/m^3]	12.2 ÷ 19.1	15.83 ÷ 23.5	–
Total energy consumption [kWh/m^3]	14.45 ÷ 21.35	19.58 ÷ 27.25	4 ÷ 6
GOR [-]	10 ÷ 16	8 ÷ 12	–
Recovery Ratio [%]	35 ÷ 45	35 ÷ 45	20 ÷ 50
Pre-Treatment	Low	Low	High

The properties for the brine and water vapor mixture (BV) are computed from the combined Gibbs free energy equation given the pressure (p), temperature (T), salinity (S) of the seawater mixture including water vapor, and boiling-brine salinity ($S_b = S(p,T)$) as:

$$g^{BV}(p,T,S) = (1-x)*g(p,T,S_b) + x*g^{Vap}(p,T).$$

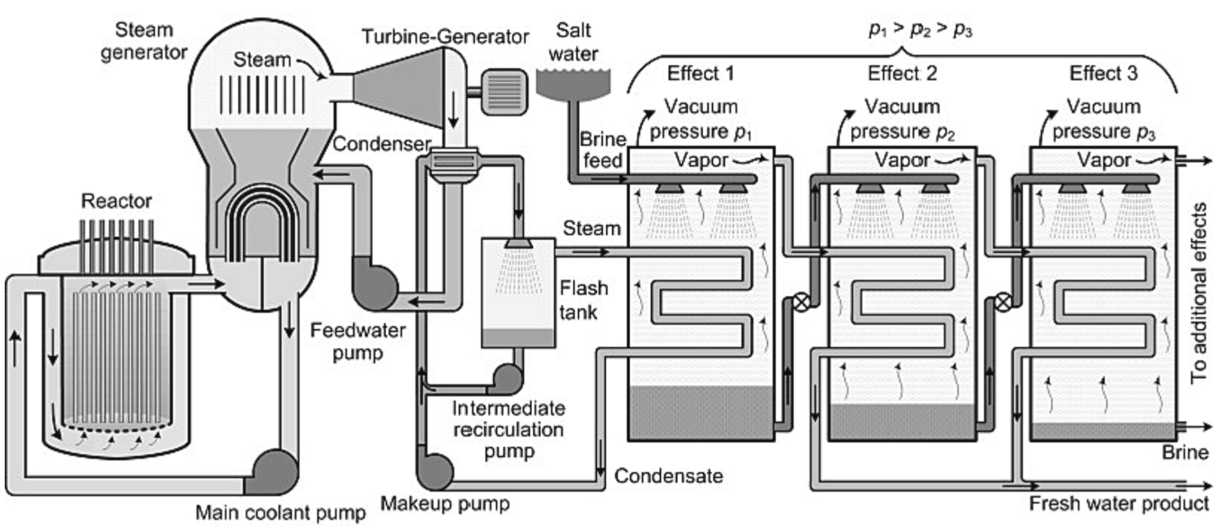

Fig. 2. Scheme of desalination plant powered with nuclear energy (courtesy from (Kazmerski and Al-Karaghouli, 2013.1016/j.rser.2012.12.064.).

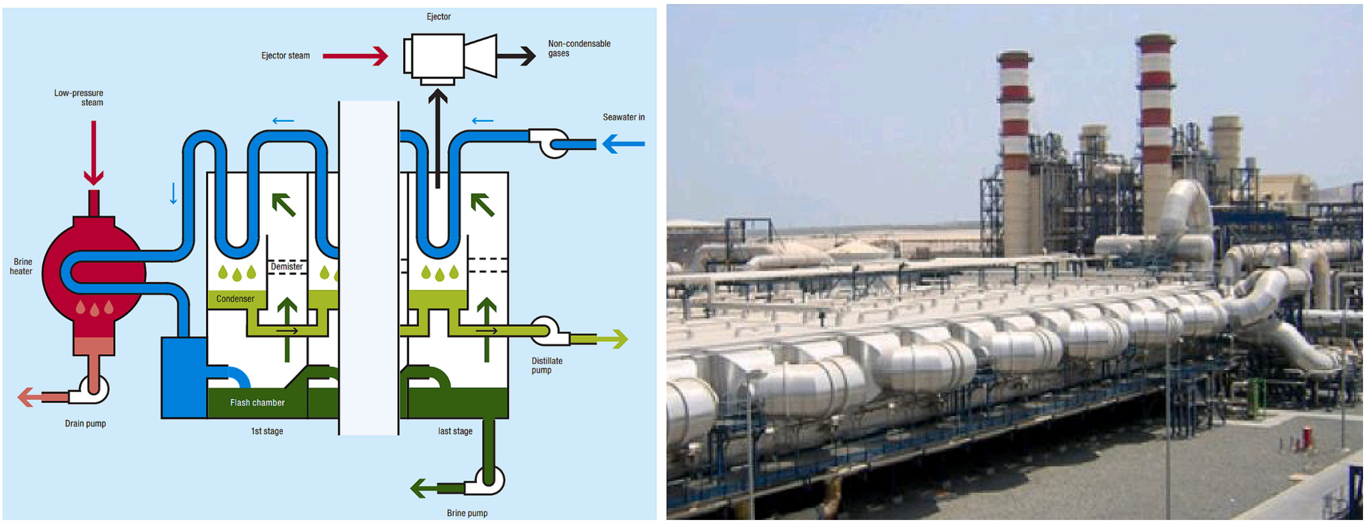

Fig. 3. MSF simple scheme (Palenzuela, Alarcòn-Padilla, & Zaragoza, 2015).

the effect pressure, secondly it is sprayed inside the effect onto the surface of the evaporator tubes, in which circulates the vapour produced in the previous effect, to form a thin film to promote and get boiling and evaporation of part of it. In this way the steam necessary for the subsequent effect and the condensate are obtained. This process is repeated all the way down the plant, whose effects gradually are operated at lower temperatures. It must be observed that the first effect instead is an exception since into it flows the steam extracted from the power plant therefore its condensate returns to the power unit. Materials like those employed in the MSF process are used. Typical operating parameters of MSF, MED and RO plants are provided in Table 2.

2.1. MSF process

MSF is almost constructed in combination with a power generating station. Its typical water capacity ranges between 10,000 m^3/d and 65,000 m^3/d.

In MSF a part of sea water vaporizes passing through multiple stages, each of which is operating at high/low pressure and temperature depending on steam thermo-hydraulic conditions. The vapour is produced by heating the seawater close to its boiling temperature and passing it to a series of stages under successively decreasing pressures to induce flashing. Then the vapour produced is condensed (and cooled as distillate) on the outside of seawater tubes of that stage and, thanks to collection tubes, it gets saved properly. Therefore, the incoming sea water is subjected to progressive heating up, passing through tubes that go through the upper part of all evaporation stages, until it reaches the operating temperature, i.e., Max Brine Temperature (MBT), in the Brine Heater (Fig. 3) where the vapour, typically extracted from one (or more) turbine stage(s), is used to heat the seawater finally up to the MBT. The discharge brine can also be partially injected by the Heat Rejection Stages in the incoming sea water to be desalinized, so that only its remainder gets discharged through the Brine Discharge line.

The components in contact with water, i.e., stages or spray plates, are made of corrosion resistant materials such as copper-nickel alloys, i.e., CuNi 90/10, or austenitic-ferritic steels, i.e., AISI 316 L, due to alkaline corrosion while the connecting pipes and the pre-heater pipes are made of titanium or copper-nickel alloys and the spray nozzles are made of polypropylene. The distilled water leaves the final stage 3 °C to 5 °C hotter than the initial salt water and with a concentration of total dissolved solids between 2 mg/l and 50 mg/l. The discharged brine has a higher temperature between 8 °C and 12 °C than the incoming saltwater temperature.

2.2. RO process

The RO process is based on the use of a semi-permeable membrane (made of e.g., cellulose acetate and polyamide) to desalinate under pressure. Seawater is forced to pass through special semi-permeable membranes: pure water is so produced with a lower concentration of salts, on average around 200 mg/l. The operating pressure ranges from 50 bar to 80 bar. The differential pressure must be high enough to overcome the natural tendency of water to move from the low salt concentration side to the high concentration side, as defined by osmotic pressure. A general scheme of RO process is shown in Fig. 4.

To increase the membrane lifetime (usually 3 years) and reduce the energy consumption, the pre-treatment phase of the incoming water, i.e., feed treatment, is essential. A post-treatment phase of the water, i.e.,

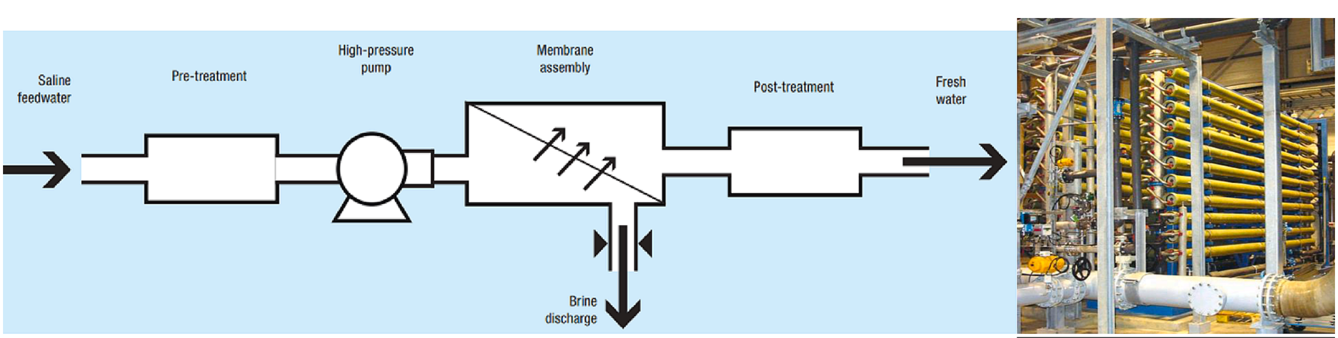

Fig. 4. RO process scheme (Schmidt and Gude, 2021).

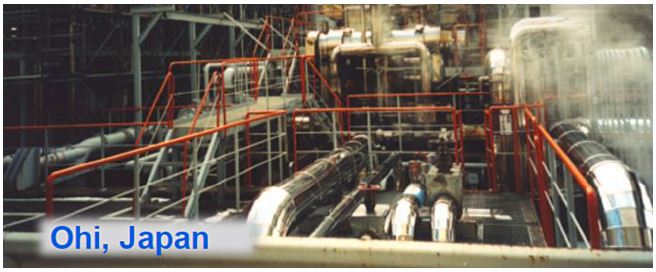

Fig. 5. DP powered with nuclear energy.

generators and for on-site supply of potable water. MED, MSF, and RO processes have been used with individual desalination capacities from 1,000 to 3,000 m^3/d. (Fig. 5)

Argentina has been working on the development of CAREM advanced small reactor coupled with RO or MED. Canada is developing instead a nuclear desalination/co-generation programme based on the integration between the CANDU reactor and the RO plant. In this latter, the discharged stream from condenser is fed as preheated feedwater to the RO system: the result is a significant improvement in RO system output, thereby reducing both capital and unit water production costs. Korea ND programme is focused on the coupling of MED-TVC with SMART reactor. The target water production capacity will be 40,000 m^3/d and the electricity generation of about 90 MWe. The integrated SMART desalination plant consists of four MED units combined with TVC. China's nuclear desalination programme involves the Nuclear Heating Reactor (NHR-200) coupled to the MED process with production capacity of 160,000 m^3/d (Wenxiang and Dazhong, 1995).[a]

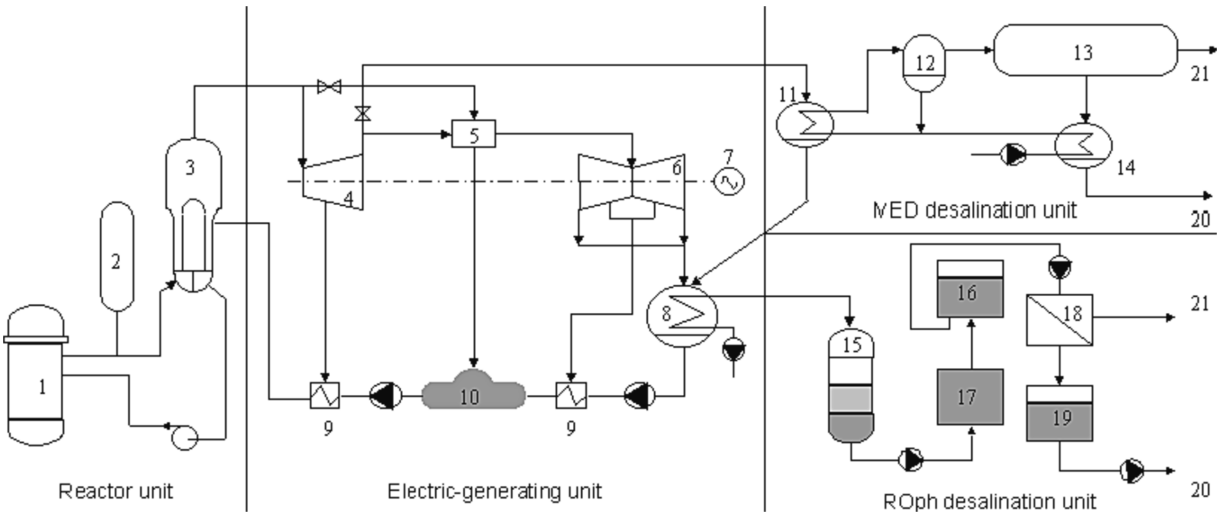

Fig. 6. Scheme of PWR-MED coupling: numbers correspond respectively to 1: Reactor core, 2: Pressuriser; 3: Steam generator; 4: High pressure turbine; 5: Intermediate steam heater; 6: Low pressure turbine, 7: Generator, 8: Main condenser, 9: Pre-heaters, 10: De-aerator; 11: Seawater heater;12: Flash tank, 13: MED plant, 14: MED output condenser, 15: Prefilter, 16: Chlorified water tank, 17: Ultra-filtration membrane, 18: RO membrane, 19: desalted water tank, 20: Fresh water out, 21: Brine out-fall (courtesy from (International Atomic Energy Agency, 2007).

product treatment, is also required to remove dissolved gases, i.e., CO_2, stabilize the pH with the addition of calcium or sodium and remove dangerous substances also from the brine. The typical capacities of RO plants vary from 0.1 m^3/d for small installations to 400,000 m^3/d for commercial uses.

2.3. Nuclear desalination plant

The adaptation of nuclear energy for desalination purposes involves the selection of technology options, which must be appropriate either to produce water and electricity or for the availability of natural and technological resources of the site hosting the plant (Avrin et al., 2018).

Technically any reactor system can be used for nuclear desalinization (ND), although several types, like the light water reactors (LWRs), have been identified as the most practical and probable for this application, because of their advanced state of development (characterized by known, widely available, and well proven technology) and deployment/use. Furthermore, among LWRs, Small Nuclear Reactor (SMRs), producing 300 MWe electrical power per reactor unit are considered as most promising: the coupling with a desalination plant is favoured by the small size, high degree of composability, and maximum flexibility in the choice of the desalination technology. Additionally, from both technical and economic point of view, nuclear desalination is particularly attractive because the continuous technical innovations and advancements may significantly lower the desalination costs (respect to conventional desalination plant).

Many countries have been started nuclear desalination programme. Integrated ND plants have been operated successfully in Japan and Kazakhstan for many years producing feedwater make-up for the steam

The existing and the planned NPPs could be used to produce fresh water using the surplus of a) waste heat (like MED with e.g., PWR, using low pressure steam extraction), b) electricity (RO with any plants, e.g., CANDU-6), and/or c) combination of heat and electricity (e.g., PHWR: steam extraction to MSF and electricity to RO). To make this (thermal coupling) possible we need to install an additional intermediate loop normally consisting of a loop with heat exchanger and a re-circulation pump. From a design point of view, this circuit should operate at a higher pressure than the NPP secondary loop to ensure that even in a hypothetical and highly improbable double rupture in the steam generator tube and the intermediate heat exchanger tube no contamination (especially tritium gas) can migrate into the desalination system. This is an important radiological safety constraint to be guaranteed constantly, with a system design avoiding any such risks. Further design limitations refer mainly to the seawater intake and outfall system and the environmental limitations with respect to temperature and salinity of seawater discharge. However, any NPP can accommodate almost any size of DPs.

The coupling (Kazmerski and Al-Karaghouli, 2013.1016/j.

[a] Broad description of the ND programme is available in the IAEA Technical Reports Series No. 400 (2000).

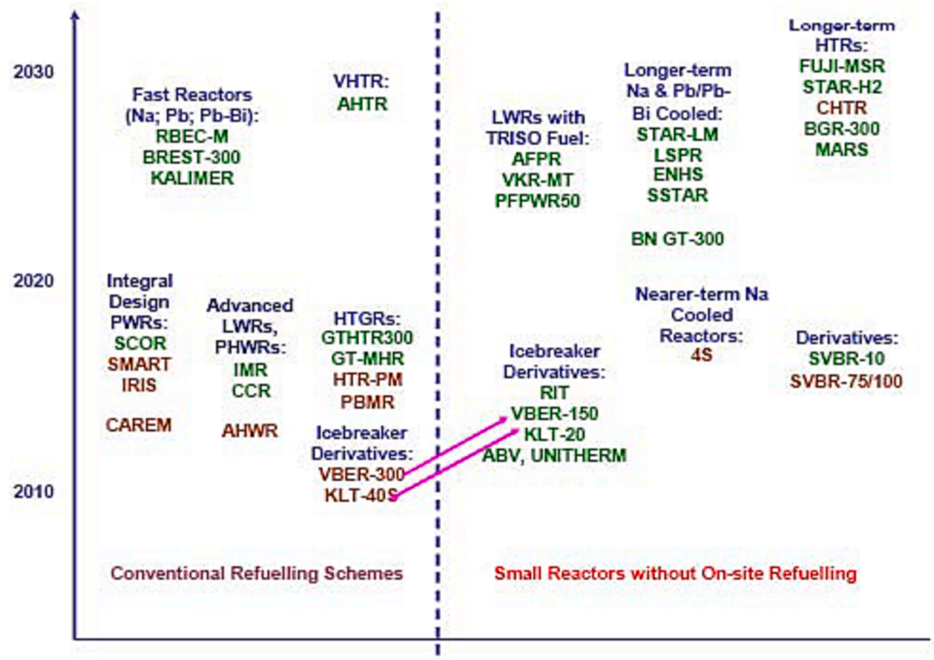

Fig. 7. SMR system considered for ND: the brown coloured name denotes those of advanced design stages, under licensing or deployment (from (Kuznetsov, 2006).

rser.2012.12.064.) between a nuclear plant and a desalination plant must be realized also in such a way as to seek the optimal thermodynamic and economic conditions, and not to impact the safety of the plant in all operating conditions (normal and accidental). Fig. 6 shows the coupling scheme of a PWR with MED system: the vapor extracted from one (or more) turbine stage(s) is fed to a heat exchanger where the temperature of incoming water increases up to 70 °C – 90 °C. Then the hot water passes through a flash tank where it is partially evaporated. This vapor is used to heat up the fluid in the first MED effect so that the MED process gets started.

3. SMR-DP: coupling and plants integration

In the past two decades a lot of studies have been focused on the feasibility of nuclear desalination (Gowin and Konishi, 1999), particularly on reliability, efficiency, cost analysis and safety aspects, since it is recognised as one of the most efficient and promising options to produce fresh water and generate power. Fig. 7 shows SMR designs considered for coupling and integration with DP.

The choice of the most appropriate DP to integrate with a nuclear plant depends on the size and type of reactor, the characteristics of the desalination process and the possibility to produce electricity (Kuznetsov, 2006 Alonso et al., 2020 Desalination,World Nuclear Association, March, 2020 Alonso, 2012 Nasiri et al., 2022 Priego, 2017), particularly:

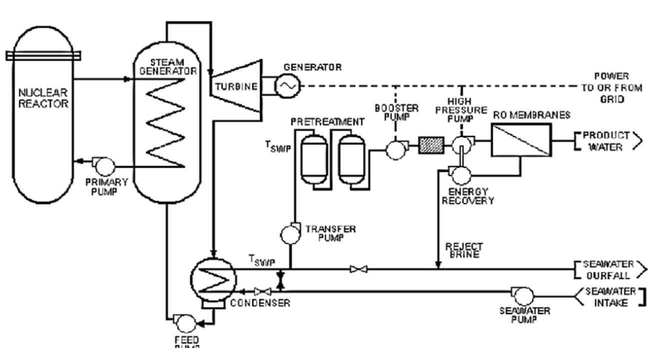

Fig. 8. Coupling between PWR and RO-DP (from (Alonso, 2012)).

- Siting conditions,
- Plant capacity and expected availability,
- Availability of water resources (quantity and quality),
- Energy resource (e.g., residual steam, waste heat, electricity), that affects the cost of energy,
- Co-generation scheme, that is selected based on technical and economic considerations,
- Materials,
- Overall cost of distribution,
- Safety,
- Quality of product water, and.
- Environmental impact assessment.

The SMR-DP coupling (Kazmerski and Al-Karaghouli, 2013.1016/j.rser.2012.12.064.) (Alonso, 2012) (Kavvadias and Khamis, 2010) must be made in such a way as:

- to seek the optimal thermodynamic and economic conditions,
- not to have an impact on the safety of the reactor in normal circumstances, in transient conditions and hypothetical accidental circumstances,
- to eliminate the probability of any radioactive release from the nuclear reactor to the desalination plant or, if this occurs, to be controlled without endangering the human health.

The coupling between the two plants requires the installation of an intermediate circuit that connects the steam coming from the nuclear plant with the thermal-type desalination plant: this represents the main difference in the connection scheme of a thermal-type desalination plant with a nuclear plant with respect to the union with a fossil fuel plant.

The intermediate circuit must be made so that it has a higher working pressure than the working pressure of the secondary circuit at the steam withdrawal point because the main purpose of the intermediate circuit is to provide a pressure barrier which, in the event of double rupture in heat exchanger tubes and steam generator, avoids any release of radioactive steam towards the desalination line. In case an event like this happens, the coupling must have a fast-acting valve that isolates the desalination plant. A desalted water monitor system also must be part of the coupling because a continuous verification and control of the

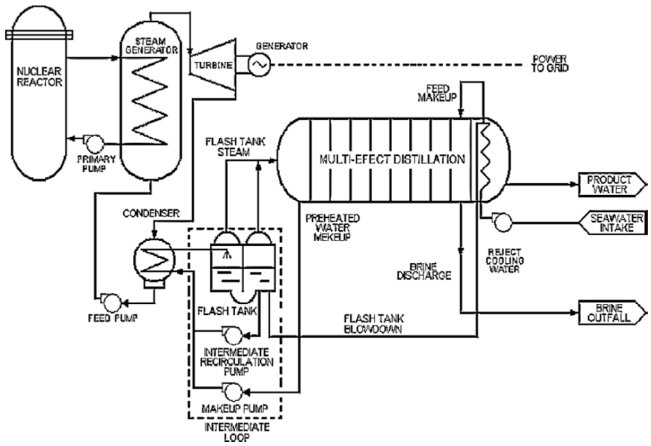

Fig. 9. Coupling between PWR and MED-DP (from (Alonso, 2012).

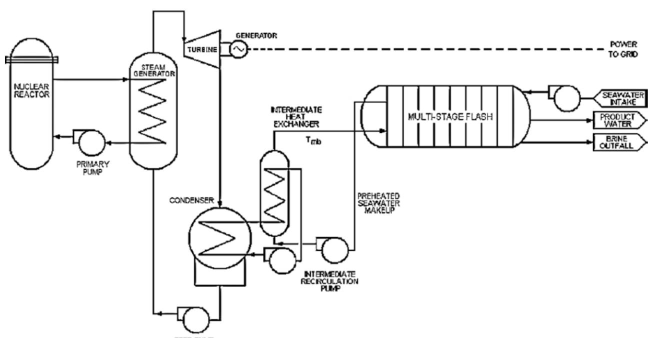

Fig. 10. Coupling between PWR and MSF-DP (from (Alonso, 2012).

potable produced water must be performed to recognize any unlikely contamination. The intermediate circuit consists either of the use of a back pressure turbine or of a heat exchanger and a recirculation pump.

Particularly, in the case of coupling with: 1) the MED process, Fig. 9, the intermediate circuit has a vaporization tank (flash tank) that acts as the first MED effect since it produces the starting steam for the MED plant; 2) the MSF process, shown in Fig. 10, the intermediate heat exchanger (IHX) can supply the hot water to feed the brine heater section.

The thermal-type union between the two plants takes place in correspondence of the secondary circuit of the reactor therefore it does not depend on the methods of production of the steam inside the primary circuit so all the reactors can supply the steam coming from the secondary circuit as a source of heat which will be used by the thermal-type desalination plant.

The steam used by the thermal type of desalination plant can be taken from the extraction points of the secondary circuit, which are located at the beginning of the secondary circuit, i.e., at the outlet of the steam generator, or before the steam enters the turbine group or in correspondence with the medium–high pressure area of the turbine group. Depending on the point of extraction, a different loss of electricity production will have to be considered in the design phase. When coupling seawater desalination plants with nuclear power plants, the risk of possible radioactive contamination of potable water produced must be made as low as achievable. Thus, at least two barriers between the reactor and the saline water are required and the so-called pressure reversal principle should be utilised.

For nuclear power plants, the steam generators are the first barrier against the transport of radioactive isotopes into the distillation plant.

When coupling the distillation plant with the nuclear power plant, the brine heater of the MSF plant and the first effect of the MED plant serve as the second barrier. In order to have the pressure reversal, the brine circulating at the brine heater of the MSF plant and the brine circulating inside the first effect of the MED plant are kept at pressure sufficiently higher than the pressure of the heating steam, so that any potential leakage in the brine heaters will be directed away from the distillation unit towards the steam power cycle.

In case of usage of extraction/condensation turbine, it is strongly recommended to adopt a more stringent provision against radioactive contamination, that is the installation of an intermediate loop. This has to be a "pressurised water isolation loop", that acts as brine heater for the MSF plant, or an open "flash-loop", that acts as the first effect for the MED plant. Both result in an additional barrier and an additional pressure reversal to prevent radioactive contamination of potable water.

In the "pressurised water isolation loop", that is made of the intermediate heat exchanger (IHX), condenser and intermediate recirculation pump, the steam coming from the turbine will be condensed in the condenser so that the latent heat of condensation will be transferred to the recirculating water that is the water that flows inside the tubes of the IHX, so that inside the IHX it can exchange heat with the incoming pressurized preheated seawater makeup (preheated seawater) that will be heated and will be sent to the first effect of the MSF plant. The operating pressure of this loop has to be lower than the pressure of the incoming preheated seawater but higher than the pressure of the steam sent in the condenser.

In the open "flash-loop", that is made of flash tank, condenser and intermediate recirculation pump, the incoming steam will be condensed in the condenser so that the latent heat of condensation will be transferred to a circulating saline water stream, which will be typically heated by 5 °C. The circulating saline water stream is made from the preheated seawater makeup (pumped by the makeup pump) added to the cooled saline water that accumulates inside the flash tank. A portion of this water flashes (boils up) in the flash tank due to its decompression: this steam is the low temperature steam that will be sent directly to the first effect of the MED plant in order to start the production of distillate. On the other hand the cooled saline water that accumulates inside the flash tank does not represent distillate because actually this water must be recirculated to the flash-loop condenser as it comes from the heat exchange with the incoming steam. Furthermore, a portion of the circulated water is continuously drawn off as brine blowdown to prevent salinity build-up. Makeup saline water is supplied from the feed stream to the circulating water to replace the losses through flashing and brine blowdown. When MED units are not in operation, the flash-loop condensers are supplied with cooling water through a bypass line to allow continuation of power plant operation.

Due to these two barriers and the pressure reversal concept, the probability of radioactive contamination of the desalted water is very low. Nevertheless, should it happen, there are further instrumentation devices that monitor radioactivity in the distillation plant and actuate systems to divert the effluents away from the mains, notify the operators and stop the process. In such a case, controlling devices that monitor the salinity of the steam power cycle of the nuclear power plant would shut down the reactor. In addition, in any case of nuclear plant with no steam generator, i.e., BWR reactor, the postulate failure scenarios will consider the release of radioactivity from the reactor core to the primary coolant system and from there through the rupture or failures in the tubes in the subsequent intermediate systems.

In the particular case of coupling with a BWR, to provide both pressure reversal and barriers against the transport of radioactive isotopes into the distillation plant, also in this case we need to implement intermediate systems just like the open "flash-loop" (MED) and the "pressurised water isolation loop" (MSF). To do that, at first a recirculation heater will be provided, in which takes place the heat exchange between the steam extracted from steam extraction points (i.e., steam lines, turbine group region, etc.) and the pressurized water circulating through the entire intermediate loop, according to the pressure reversal concept. Then a subsequent heat exchange occurs inside either the flash

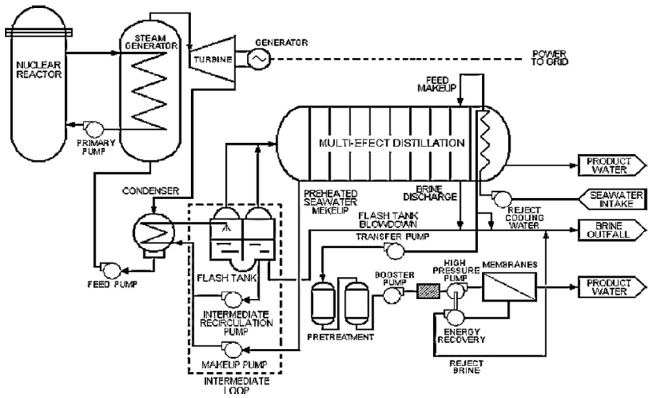

Fig. 11. Coupling between PWR and hybrid MED + RO-DP (from (Alonso, 2012).

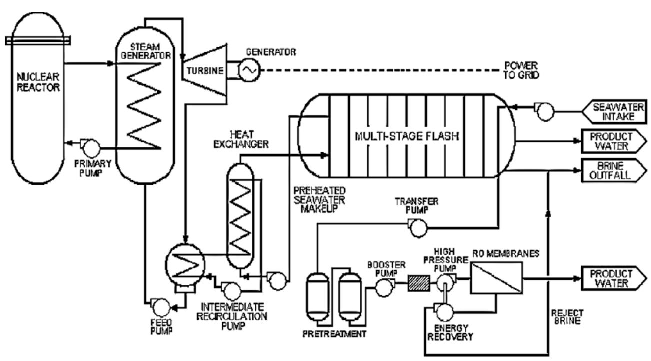

Fig. 12. Coupling between PWR and a hybrid MSF + RO-DP (from (Alonso, 2012).

tank (MED) or in the intermediate heat exchanger (MSF).

The union between a nuclear plant and a membrane desalination plant, as shown in Fig. 8, is simple because it only requires an electrical connection: for this reason, the risk that a possible radioactive contamination reaches the desalinated water is practically nil. The cases of nuclear plant connected with a hybrid desalination plant are shown in Fig. 11 and Fig. 12. In both cases we observe the presence of the intermediate circuit for the connection with the thermal desalination plant and the connection in series with the membrane desalination plant, which is electrically connected with the nuclear plant, and which treats the waste brine deriving from the thermal process. In the case of parallel connection, on the other hand, separate inlets are required for the salt water which must be treated exclusively by the thermal desalination plant, always connected to the nuclear plant via an intermediate circuit, and for the salt water which must be treated exclusively by the membrane plant, always electrically connected to the nuclear plant. The design life of the integrated system must be comparable with the operational life of the desalination plant.

In this paper, the ND feasibility of CAREM25 and SMART reactors was investigated numerically by DEEP software. CAREM25 is an advanced and flexible SMR based on modular new design solutions involving the electrical and thermal coupling of desalination technology. It is characterised by an integral design of the primary circuit; the flow rate in the reactor primary systems is maintained by natural circulation (Nasiri et al., 2022). CAREM plant has a standard steam cycle: steam is superheated under all plant conditions and no super-heater is needed. SMART is an integral reactor system as well, with 330 MWth thermal power. It differs from the loop-type reactors for the arrangement of its primary components. The main interest in the coupling SMART to DP is related to the utilization of steam rather than electricity: ND would produce 40 000 m^3/day of desalted water (sufficient for a population of 100,000 people) (Priego, 2017).

Table 3
Input data.

Input value	CC GAS	CAREM25	SMART
Reference Thermal Power [MWth]	65	100	312.5
Reference Net Efficiency [%]	53.35	32	32
Water Salinity [ppm]	34,000	34,000	38,500
Water Temperature [^{o} C]	15	15	21
Water Capacity [m^3/d]	48,000	48,000	40,000
Discount Rate [%]	6	6	6
Interest Rate [%]	6	6	6
Fuel Escalation [%]	–	–	–

3.1. Deep evaluation

The feasibility analysis of ND with the CAREM25 and SMART reactors was carried out by means of the Desalination Economic Evaluation Program (DEEP), which is a software developed by the IAEA (Al-Othman, 2019). DEEP efficiency and validity have been certified during the approval and release phase of the software by the IAEA (starting from the 90 s up to the most recent version). The model results seem consistent with current practice as the water costs fall into the expected range found in literature. As an example, the GOR values calculated with the DEEP demonstrated to be in good agreement (deviation lesser than 3.5 %) with the other experimental and numerical values (DEEP, 2000; Kavvadias and Khamis, 2010).

DEEP allows designers and decision makers: 1) to compare the performance of several design alternatives on a consistent basis with common assumptions, 2) to estimate approximately the cost of desalinated water and power as a function of quantity and site-specific parameters including temperatures and salinity, and 3) to identify the lowest cost options for providing specified quantities of desalinated water and/or power at a given location.

The desalination options of the DEEP software include MSF, MED, RO and hybrid systems MED + RO e MSF + RO with separate inlets, while power options include nuclear, fossil and renewable sources. Both co-generations of electricity and water as well as water-only plants can be modelled.

The input data are the desalination configuration, power, and water capacities as well as values for the various basic performance and costing data.

The results of the technical–economic analyses carried out for each selected option include:

- levelized cost of electricity and levelized cost of desalted water as a function of site-specific parameters, energy source, amount of power produced, power production technology, desalination technology and amount of desalted water produced,
- power cost and water cost breakdowns,
- energy consumption and the net power that can be allocated to the grid,
- side-by-side comparison of many design alternatives on a consistent basis with common assumptions collected in a single graphical interface,
- quick identification of the lowest cost options for providing specified quantities of desalted water and/or power at a given location.

In what follows the economics of nuclear desalination are presented. It is worthy to remark that the uncertainty associated to the obtained results is less than 3.5 % (DEEP, 2000).

The input data of the analyses we carried out are provided in Table 3, while Table 4 and Table 5 provide some of the important data of coupled plants. Fig. 13 shows the comparison of several possible coupling scenario provided by DEEP. Lastly, Table 8 summarises the main results obtained. Furthermore, it has been conducted a similar analysis also for

Table 4
Power plants input data.

Input Data	CC GAS	CAREM25	SMART
Main Steam Temperature [° C]	290	290	296
Auxiliary Loads [%]	5	5	5.3
Specific Construction Cost [$/kW]	700	1500	1714
Specific Fuel Cost [$/MWh]	51	7.2	8
Specific O&M Cost [$/MWh]	5.5	9.4	5.59

Table 5
DP main input data.

Desalination Plant	RO	MED	MSF
Max Brine Temperature [° C]	–	65	110
Membrane Pressure [bar]	69	–	–
In/Outfall Specific Cost Factor [%]	7	7	10
Operational Availability [%]	90	90	90
Base Unit Cost [$/m^3]	900	900	1000

a gas-fired combined cycle plant CC GAS system in order to directly compare this widely used power unit with the proposed ND systems. Specifically, it has been chosen a CC GAS producing the same electrical power produced by CAREM25.

Fig. 13 shows a graphical comparison between the different case scenarios investigated, from which it can be rapidly identified the contribution of the different costs and the most or least expensive layouts.

An estimation of the lower and upper limits of investment and total water cost for various DP projects has been also carried out, the outcomes of which (see Table 6) highlight that for the wide-range thermal-based desalination process the total water costs are 0.7–1.2 $/m^3 for MED, and 0.8–1.5 $/m^3 for MSF while for the RO process the cost is 0.5–1.2 $/m^3. Nevertheless, it is crucial to note that in comparing costs, the total energy utilization for each process is a more realistic factor since, particularly in thermal-based systems, energy is greatly subsidized by governments in energy-abundant countries, making the total water cost an inefficient factor for comparing cost between plants built in various countries.

Lastly, Table 7 shows the comparison in terms of water costs between the conventional and nuclear desalination technology. For this latter, the data are those obtained from DEEP analyses. From the comparison it appears that the water cost from the DEEP analysis is competitive with the average values, especially with regards to the RO process. Indeed, the advantage in terms of guaranteeing the production of a high quantity of electricity stands out even more since the amount of energy required by the RO system for its operation is very small compared to the power produced by the reactor and destined for the electricity grid given that there is no direct subtraction of steam for desalination purposes. On the other hand, conventional DPs are certainly favoured by the possibility of being more easily installed, as they are conventional systems, but they still need an external energy source to operate.

As for the CC GAS system compared to the ND obtainable with CAREM25, results in Fig. 14 show that globally: 1) the fuel cost shares 80 %, 2) the O&M cost shares 6.7 % and 3) the annual capital cost shares 13.3 % of the annual management expenses. It can also be seen that the summation of the specific annualized capital cost to the specific annual operating cost provides the power cost of 0.064 $/kWh, which in this case is strongly due to the fuel cost contribution, which represents the gas supply cost.

From the analysis of data of Fig. 15 we observe that globally: 1) the fuel cost shares 20 %, 2) the O&M cost shares 26 % and 3) the annual capital cost shares 54 % of the annual management expenses. Moreover, the summation of the specific annualized capital cost and the specific annual operating cost provides the power cost of almost 0.036 $/kWh,

Table 6
Average water cost and energy consumption for DP.

Energy / Cost	Conventional Desalination Technology		
	RO	**MED**	**MSF**
Electrical energy[kWh/m^3]	4–6	2–2.5	2.5–5
Thermal energy [kWh/m^3]	–	12.2–19.1	15.83–23.5
Total energy [kWh/m^3]	4–6	14.45–21.35	19.58–27.25
Investment cost [$/m^3/d]	900–2500	900–2000	1200–2500
Total water cost [$/m^3]	0.5–1.2	0.7–1.2	0.8–1.5

Table 7
DP: average water cost and energy consumption.

DP	Water cost [$/m3]
MSF	1.44
MED-TVC	1.39
RO Red Sea	1.38
RO Arabian Gulf	1.35
RO Mediterranean Sea	0.98
Hybrid MSF/MED	1.15
Hybrid RO	1.03
ND	**Water cost [$/m^3]**
SMART MSF	1.12
SMART MED	0.81
SMART RO	0.63
SMART MED + RO	0.68
SMART MSF + RO	0.8
CAREM25 RO	0.64

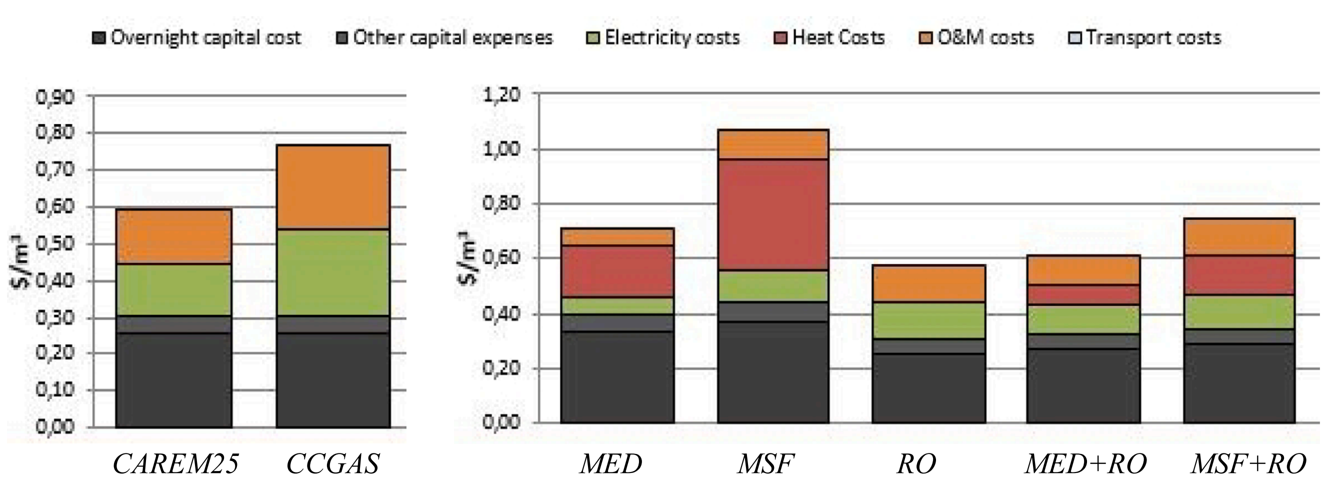

Fig. 13. Side-by-side comparison (from software DEEP).

Power Plant	
Type	Combined Cycle Gas (CC GAS)
Reference thermal output	60 MW(th)
Reference electricity output	31.95 MWe
Site Specific Electricity Production	277 GWh/yr
Availability	90%

Capital Costs of Power Plant	Total (M$)	Specific($/kW)	Share
Overnight EPC costs	22	700	83%
Owners costs	2	70	8%
Contigency cost	-	-	0%
Interest during construction	2	70	8%
Decommissioning costs	-	-	0%
Total Capital Costs	27	840	
Annualized Capital Costs	2	56	
Sp. Annualized Capital Costs		0,008	

Operating Costs of Power Plant	Total (M$)	Specific ($/kWh)	Share
Fuel Costs	12	0,051	90%
Operation & Maintenance costs	1	0,006	10%
Carbon tax	-	-	0%
Annual Operating costs	13	0,057	

TOTAL ANNUAL COST	16	M$
Power Cost	0,064	$/kWh

Fig. 14. CC GAS power cost breakdowns (from software DEEP).

which in this case is strongly due to the annual capital costs contribution, which represents the annual capital cost of the power plant.

SMART reactor power cost breakdowns (as obtained from software DEEP) highlighted that globally 1) the fuel cost shares 22.2 %, 2) the O&M cost shares 16.7 % and 3) the annual capital cost shares 61.1 % of the annual management expenses. It can also be seen that the summation of the specific annualized capital cost to the specific annual operating cost provides the power cost of 0.036 $/kWh, which in this case is strongly due to the annual capital costs contribution, which represents the annual capital cost of the power plant.

The flow diagram obtained with the DEEP software offers a schematic representation of the incoming and outgoing flows, reporting some inputs data and output outcomes. In the following a short description of them is provided.

In the flow diagram of Fig. 16, the green line indicates the electrical connection between the power system and the RO plant. It is observed that of the theoretical 32 MWe, considering the capacity factor of just over 90 % and the 1 MWe transferred as electricity necessary for the auxiliary loads of the plant, we obtain that of the 28 MWe available 21 MWe are destined for the electrical grid and 7 MWe move to the RO plant. The red line is the steam extracted from the secondary circuit of the nuclear plant that is directed to the turbine group. In this case of extraction/condensation turbine all the steam works at the turbine so that, out of the turbine, the exiting steam will be condensed at the condenser so that this condensate can move back to the reactor. The blue lines indicate respectively the income line of the salt water into RO plant, the outcome line of the brine and the common exit of the permeate in order to obtain the desalinated water having the typical salinity of about 200 ppm.

It can be carried out a similar description for the flow diagram of Fig. 18, starting from the theoretical 100 MWe, considering the capacity factor of just over 90 % and the 5 MWe transferred as electricity necessary for the auxiliary loads of the plant, we obtain that of the 87 MWe available 81 MWe are destined for the electrical grid and 5.8 MWe move to the RO plant. It has been noted from the flow diagram of Fig. 17 that the gas-fired combined cycle plant directly produces the majority of the electricity that has to move to the electrical grid. In addition, 9 MWe are produced by the turbine so that, of these 9 MWe, also considering a small amount of MWe due to the auxiliary loads, 7 MWe move to the RO plant are obtained. So finally, it has been obtained the total amount of 22 MWe that has to feed the electrical grid.

In the flow diagram of Fig. 19, the green line indicates the electrical connection to the electrical grid and to the MED plant. It is observed that of the theoretical 100 MWe, considering the capacity factor of just over 90 % and the 5 MWe transferred as electricity necessary for the auxiliary loads of the plant, we obtain that of the 87 MWe available, due to the

Power Plant	
Type	Steam Cycle - Nuclear
Reference thermal output	100 MW(th)
Reference electricity output	32 MW(e)
Site Specific Electricity Production	223 GWh/yr
Availability	90%

Capital Costs of Power Plant	Total (M$)	Specific($/kW)	Share
Overnight EPC costs	48	1.500	74%
Owners costs	5	150	7%
Contigency cost	-	-	0%
Interest during construction	5	151	7%
Decommissioning costs	7	225	11%
Total Capital Costs	65	2.026	
Annualized Capital Costs	4	135	
Sp. Annualized Capital Costs		0,019	

Operating Costs of Power Plant	Total (M$)	Specific ($/kWh)	Share
Fuel Costs	2	0,007	43%
Operation & Maintenance costs	2	0,009	57%
Carbon tax	-	-	0%
Annual Operating costs	4	0,017	

TOTAL ANNUAL COST	8	M$
Power Cost	0,036	$/kWh

Fig. 15. CAREM25 reactor power cost breakdowns (from software DEEP).

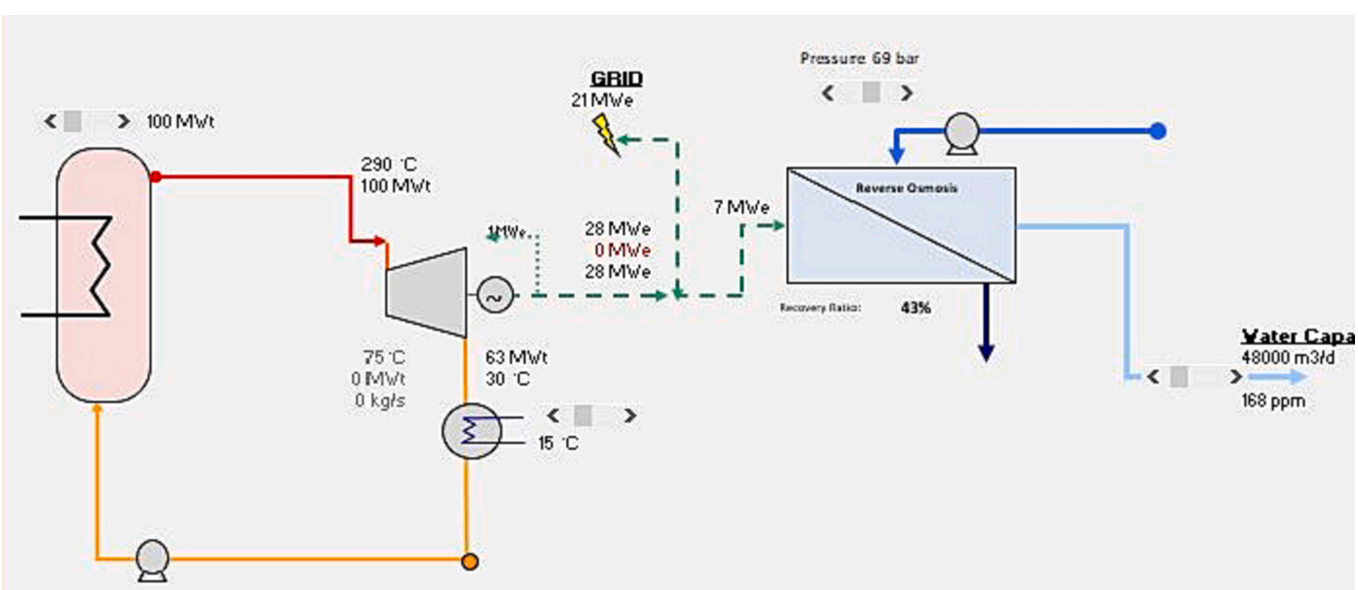

Fig. 16. Flow Diagram of CAREM + RO (from software DEEP).

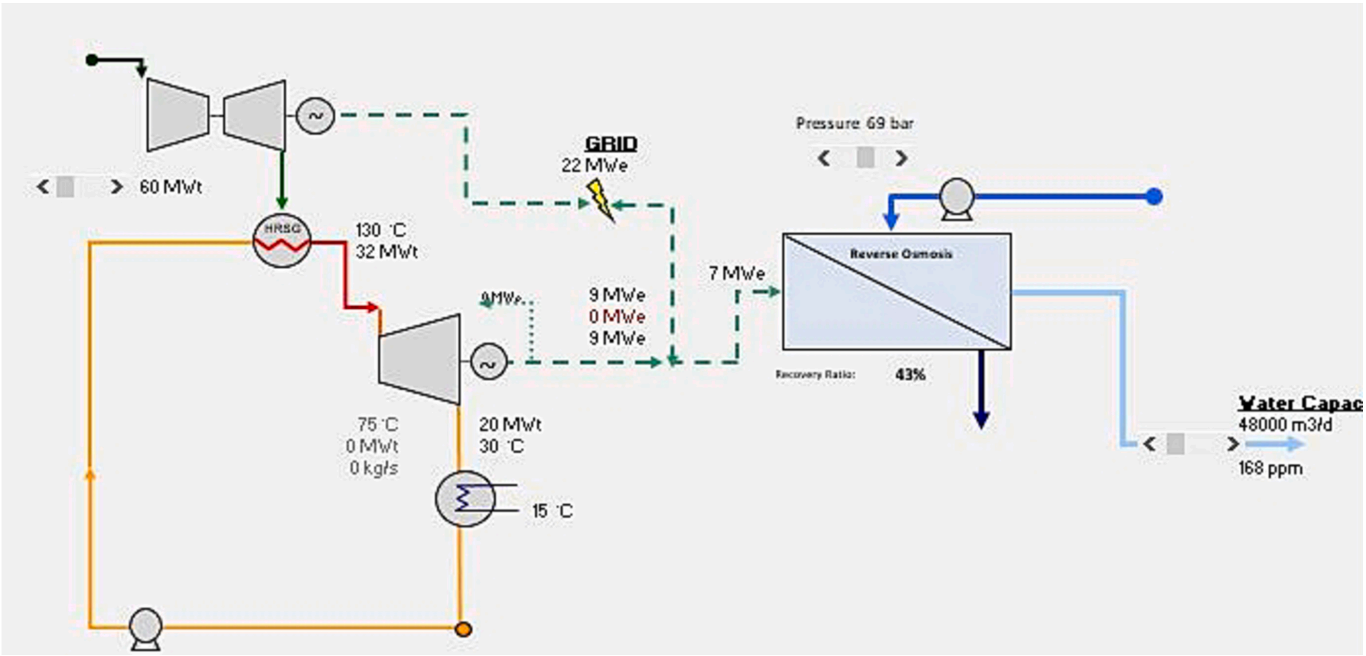

Fig. 17. Flow Diagram of CC GAS + RO (from software DEEP).

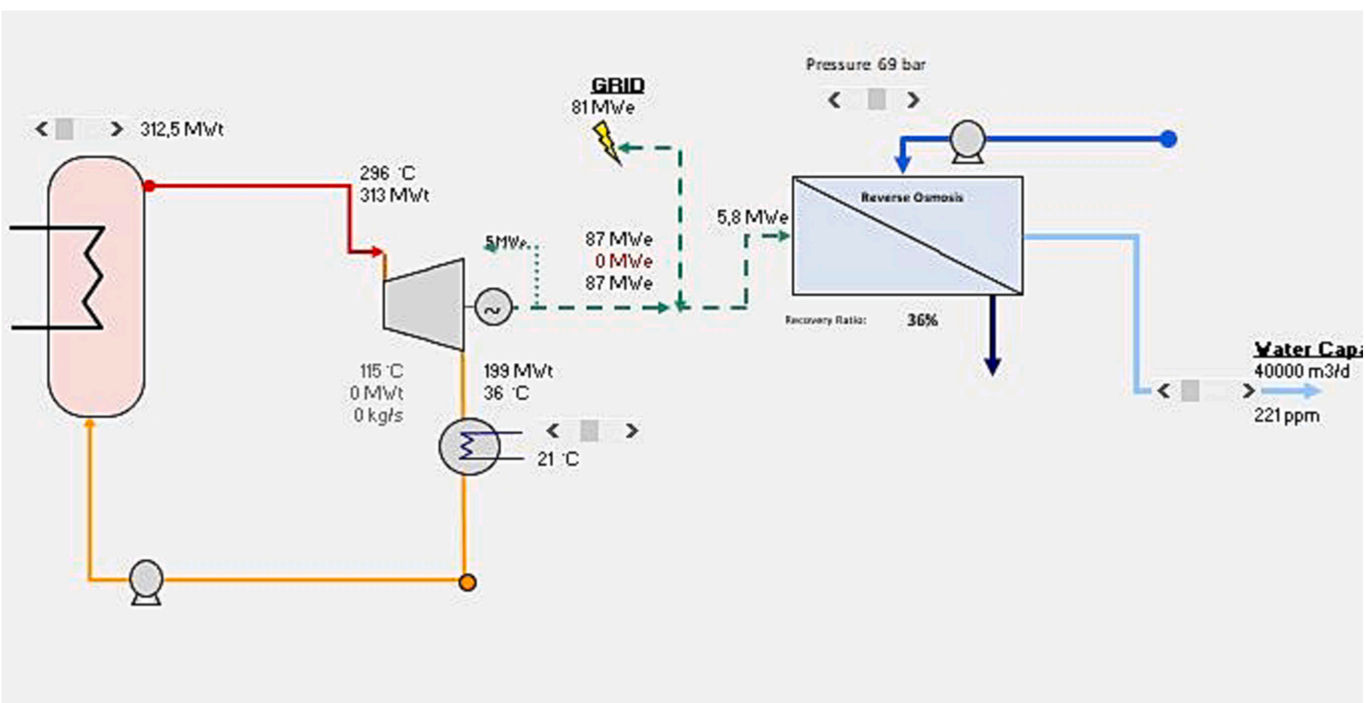

Fig. 18. Flow Diagram of SMART + RO (from software DEEP).

withdrawal of steam necessary for the MED plant 9 MWe are released, therefore 78 MWe are available, which are divided between 75 MWe destined for the electrical grid, 2.6 MWe move to the MED plant.

The red line is the steam extracted from the secondary circuit of the nuclear plant that is directed to the turbine group. As it can be observed, the intermediate circuit is shown in the lower part of the diagram, and it gives a simplified scheme of the real intermediate circuit described in section 3.

It is characterized by the incoming orange line, which is the steam extracted from the turbine, and the outgoing orange line, which in the MED case already indicates the steam obtained in the real intermediate loop that is destined for the MED plant. The incoming steam that has been condensed inside the intermediate circuit joins the steam exiting from the turbine group as condensate and their blend will be introduced into the reactor following the common orange line. It is worthy to note in addition that in the intermediate circuit, the overall temperature difference exchanged between its inlet and outlet is equal to almost 5 °C, and the power of the pump that must insert the pressurized water, which must give sufficient pressure to guarantee pressure reversal. The blue lines indicate respectively the income line of the salt water into the MED

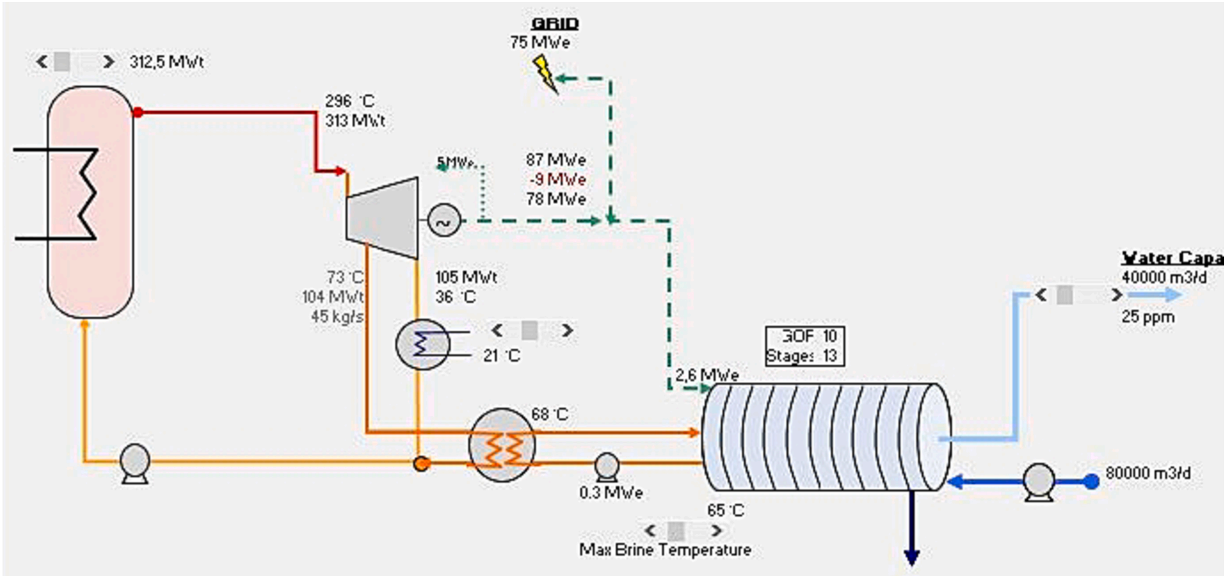

Fig. 19. Flow Diagram of SMART + MED (from software DEEP).

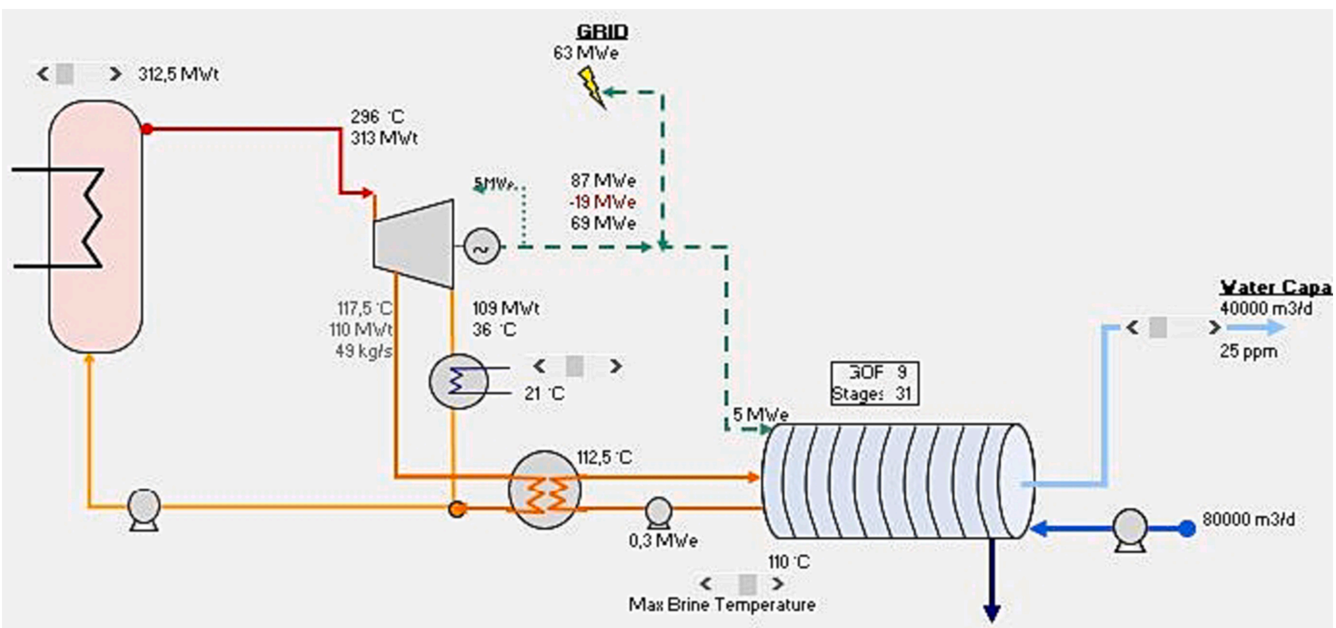

Fig. 20. Flow Diagram of SMART + MSF (from software DEEP).

plant, the outcome line of the brine and the exit of the permeate having the typical salinity of 25 ppm.

In Fig. 20, the green line indicates the electrical connection to the electrical grid and MSF plant. Considering a capacity factor of just over 90 %, of the theoretical 100 MWe 5 MWe are transferred as electrical energy necessary for the auxiliary loads of the plant and 19 MWe are absorbed by the MSF plant, we obtain 69 MWe, which in turn are divided between the electricity grid (63 MWe) and the MSF plant (5 MWe) respectively. The red line is the steam extracted from the secondary circuit of the nuclear plant that is directed to the turbine group. As it can be observed, the intermediate circuit is located in the lower part of the diagram, providing a simplified scheme of the real intermediate circuit described in detail in section 3. It is characterized by the incoming orange line, which is the steam extracted from the turbine, and the outgoing orange line, which in the MSF case indicates the water coming out of the brine heater, i.e., coming out of the real intermediate loop and destined for the MSF plant. The incoming steam that was condensed inside the intermediate circuit joins the steam exiting from the turbine group as condensate and their blend will flow into the reactor (orange path in Fig. 20). In the intermediate circuit, the overall temperature difference between inlet and outlet is almost 5 °C. The blue lines represent respectively the saltwater inlet into the MSF plant, and the outlet of the brine and permeate, which has typical salinity of 25 ppm.

In Fig. 21, the green line represents the electrical connection between the power system and the MSF and RO plant. It was observed that similarly to the previous case, of the theoretical 100 MWe, only 74 MWe are dispatched on the electric grid, since 3.5 MWe are used by the RO plant, and about 1.9 MWe are used by the MSF plant. The red line represents the steam path towards turbine, while the intermediate

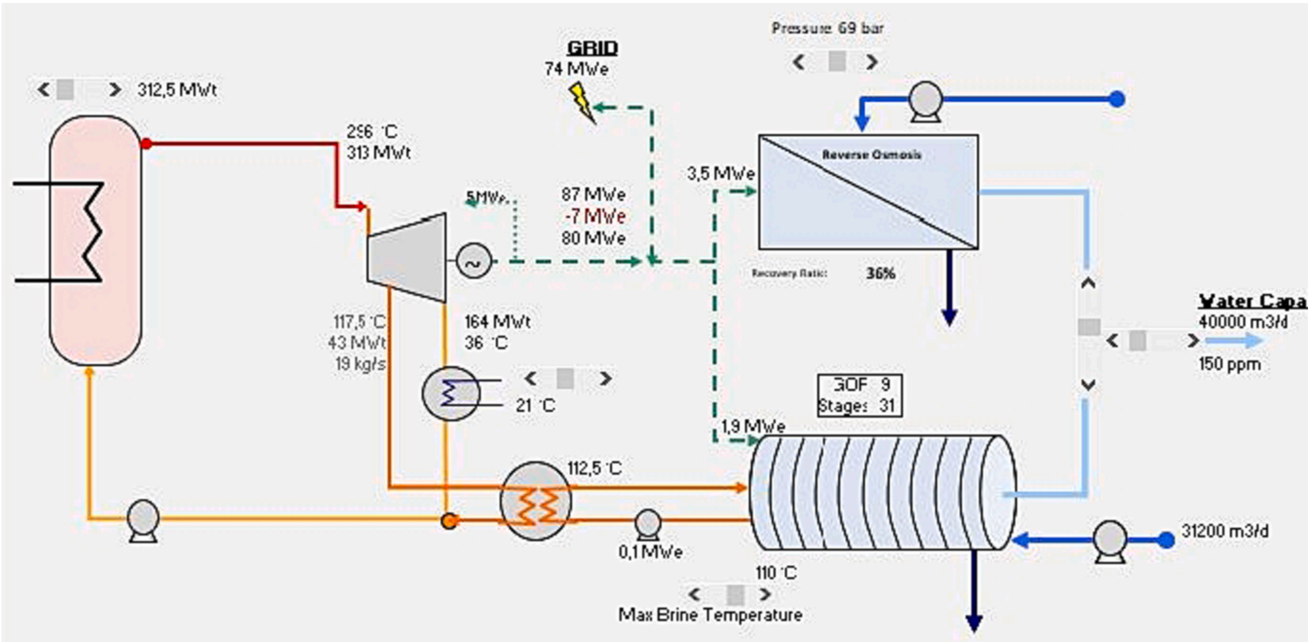

Fig. 21. Flow Diagram of SMART MSF + RO (from software DEEP).

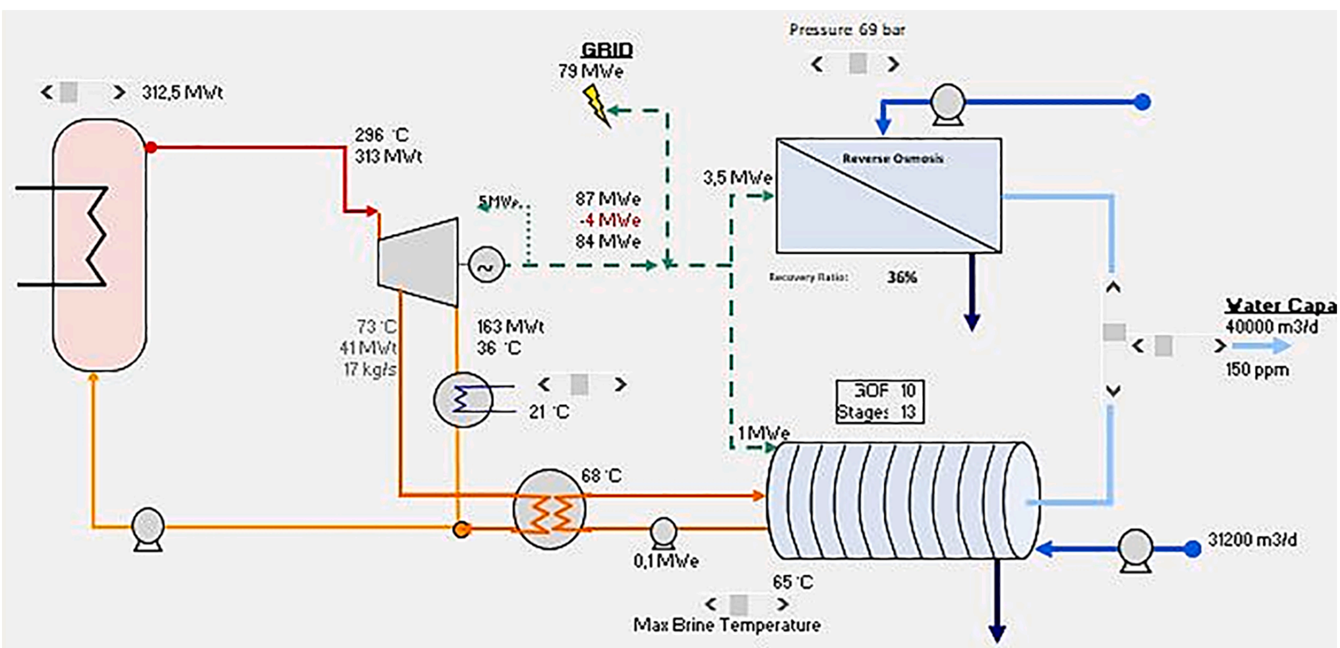

Fig. 22. Flow Diagram of SMART MED + RO (from software DEEP).

circuit is shown in the lower part of the diagram. It is characterized by an incoming orange line, that is the steam extracted from the turbine, and the outlet orange line, which in the MSF case indicates the water coming out of the brine heater. The incoming steam that has been condensed inside the intermediate circuit joins the steam exiting from the turbine group as condensate and their blend will be introduced into the reactor following the common orange line. The blue lines represent respectively the saltwater inlet to MSF and RO plants, the brine and the common permeate outlet, which mixes the two permeates turning out water having salinity of 150 ppm.

Similarly, in Fig. 22, the flow diagram in case of hybrid MED and RO is represented. The green line indicates the electrical connection between the power system and the MED and the RO plant. It is observed that of the theoretical 100 MWe, considering the capacity factor of just over 90% and the 5 MWe transferred as electricity necessary for the auxiliary loads of the plant, we obtain that of the 87 MWe available, due to the withdrawal of steam necessary for the MED plant 4 MWe are released, therefore 84 MWe are available, which are divided between 79 MWe destined for the electrical grid, 3.5 MWe move to the RO plant, 1 MWe move to the MED plant. The red line is the steam extracted from the secondary circuit of the nuclear plant that is directed to the turbine group. The intermediate circuit is characterized by an incoming orange line, that is the steam extracted from the turbine, and the outlet orange line, which in the MED case indicates the vapour coming out of the flash

Desalination Plant	
Type	RO
Total capacity	48000 m^3/d
Feed salinity	34000 ppm
Combined availability	81%
Water Production	15,77 M m^3/yr
Power Lost	0 MW(e)
Power used for desalination	7 MW(e)

Capital Costs of Desalination Plant	MSF	RO	Total (M$)	Specific ($/m3 d)	Share
Construction Cost	-	46	45	963	79%
Intermediate loop cost	-	-	-	-	0%
Backup Heat Source	-	-	-	-	0%
Intal/Outfall costs	-	-	4	77	6%
Water plant owners cost	-	2	2	48	4%
Water plant contingency cost	-	5	5	101	8%
Interest during Construction	-	2	2	33	3%
Total Capital Costs	-	55	59	1222	
Annualized Capital Costs			5		
Sp. Annualized Cap Costs				0,30	$/m3

Operating Costs of Desalination Plant	MSF	RO	Total (M$)	Specific ($/m3)	Share
Energy Costs					
Heat cost	-		-	-	0%
Backup heat cost	-		-	-	0%
Electricity cost	-	3,2	3,2	0,20	48%
Purchased electricity cost	-	0,5	0,5	0,03	7%
Total Energy Costs	-	4	4	0,23	55%
Operation and Maintenance Costs				-	0%
Management cost	-	-	0,13	0,01	2%
Labour cost	-	-	0,50	0,03	8%
Material cost	-	2,06	2,1	0,13	31%
Insurance cost	-	0,27	0,3	0,02	4%
Total O&M cost	-	2	3	0,19	45%
Total Operating Costs	-	6	7	0,42	

Total annual cost	11,43	M$
Water production cost	0,725	$/m³
Water Transport costs	-	$/m³
Total water cost	**0,725**	**$/m³**

Fig. 23. Overview of the water cost breakdowns related to CC GAS coupled to RO.

tank. The incoming steam that has been condensed inside the intermediate circuit joins the steam exiting from the turbine group as condensate and their blend will be introduced into the reactor following the common orange line. The blue lines represent respectively the saltwater inlet to MED and RO plants, the brine and the common permeate outlet, which mixes the two permeates turning out water having salinity of 150 ppm.

Fig. 23 shows e.g., the water cost breakdowns for a CC GAS-RO plants coupling. Particularly it is possible to observe that: 1) the power cost accounts for 33 %, 2) the annualized capital cost accounts for 43 %, 3) the material cost accounts for 18.6 % and 4) the labour and management cost account for 5.4 %. It can also be seen that the total water cost is almost 0.73 $/m^3 and the majority of the annual costs is due to the annualized capital cost, which represents the annual capital cost of the desalination plant connected to the gas-fired combined cycle plant and for sure the percentage of the power cost increases since the gas fuel cost is greater than the nuclear fuel cost. Table 8 shows in a more compact manner the main results of all the performed analyses.

As for CAREM25 case of study concerned, we observed that the thermal power produced is not sufficient for the required water capacity using thermal desalination processes. Therefore, the only way to guarantee the expected water production is through RO desalination process. The cost of the electrical power produced is greater in the case of the CC GAS power plant since the larger value of “Specific Fuel Cost” determines this difference, even if the value of “Specific Construction Cost” of the CC GAS power plant is approximately half of the similar cost for the CAREM25. In addition, it must be considered the highly probable fuel escalation of the gas fuel cost during the plant lifetime, that is opposite to the strong stability of the nuclear fuel cost, which is constant, so that in the CC GAS case there may be sudden increases in both power cost and water cost. Lastly, the large difference in terms of lifecycle emission must be considered, since it is clearly in favour of the CAREM25 power plant choice.

As to SMART case of study, we noted that the variation of the electrical power that can be dispatched to the electricity grid due to the withdrawal of part of the steam from the power cycle according to the type of desalination plant connected to the reactor. This extraction determines the “Power Lost” in all distillation plants. On the other hand, for the RO system the “Power Lost” is zero because it needs only the electrical power. This “Power Lost” entails the increase in the cost of water production, represented by the “Heat Cost”, as it is shown in the previous graphs.

The impact of the “Heat Cost” on the O&M cost of water that is produced by the different desalination plant layouts connected to the SMART nuclear plant is equal to 49 % in MED, 59 % in MSF, 20 % in MED + RO, 32 % in MSF + RO.

Starting from the same salinity of the produced water, these analyses recommend choosing the RO, MED and MED + RO processes whether we decide to produce both more energy and more water at the same plant.

4. Summary

This paper describes the various aspects of nuclear desalination processes including the different nuclear reactors used, the trends, and economic assessments for on-site ND plants.

It was described and demonstrated that the nuclear desalination presents an environmentally sound option for addressing water shortages. The amount of CO_2 emissions produced by a ND plant could be up to 150 times lower than those produced by the same desalination plant having the widely used gas-fired combined cycle plant as power unit. Nuclear energy also includes the benefits that co-location of power and desalination facilities offers in terms of intakes/outtakes and infrastructures for connection to the electricity grid.

SMRs confirmed to be very promising compared to other conventional energy sources as they can produce large amount of water even with a lower power reactor, like in the case of the CAREM25, and of large quantities of electricity and water for both industrial and domestic use, with a higher power reactor, like in the case of the SMART.

Effectively if we consider the average per capita consumption of electricity and water, respectively estimated at 4.7 MWh/y and at 80.3 m^3/y, and the preferred desalination method of producing domestic water, i.e., RO technique, we can say that CAREM25 reactor coupled to a RO desalination plant can produce electricity for 35,000 inhabitants and water for domestic use for 200,000 inhabitants. SMART reactor coupled to a RO desalination plant can produce instead electricity for 130,000 inhabitants and water for domestic use for 160,000 inhabitants.

CRediT authorship contribution statement

Renato Buzzetti: Conceptualization, Formal analysis, Investigation, Software, Writing – original draft, Writing – review & editing. **Rosa Lo Frano:** Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. **Angelo Salvatore Cancemi:** Data curation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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